Description

Superconductor device having a superconductive magnet and a refrigeration unit

The invention relates to a superconductor device

- having a magnet which contains at least one superconductive winding without any refrigerant,
- having a refrigeration unit which has at least one cold head,

and

- having means for thermal coupling of the at least one winding to the at least one cold head.

Corresponding superconductor devices are known, for example, from "Proc. 16th Int. Cryog. Engng. Conf. [ICEC 16]", Kitakyushu, JP, 20. May 24, 1996, Verlag Elsevier Science, 1997, pages 1109 to 1132.

In addition to metallic superconductor materials such as NbTi or Nb_3Sn, which have been known for a very long time and have very low critical temperatures T_c, and which are therefore also referred to as low-T_c superconductor materials or LTC materials, metal-oxide superconductor materials with critical temperatures T_c above 77 K have been known since 1987. The latter materials are also referred to as high-T_c superconductor materials or HTC materials.

Attempts have also been made to produce superconductive metal magnet windings with conductors using such HTC materials. Because their current carrying capacity in magnetic fields has until now been relatively poor, in particular with inductions in the Tesla range, the conductors of such windings are often nevertheless kept at a temperature below 77 K, for example between 10 and 50 K, despite the intrinsically high critical temperatures T_c of the materials used, in order

in this way to make it possible to carry significant currents with relatively strong field strengths, for example of several Tesla.

Refrigeration units in the form of so-called cryogenic coolers with a closed helium compressed gas circuit are preferably used to cool windings with HTC conductors in the stated temperature range. Cryogenic coolers such as these are, in particular, of the Gifford-McMahon or Stirling type, or are in the form of so-called pulse tube coolers. Refrigeration units of this type furthermore have the advantage that the refrigeration power is effectively available at the push of a button, so that there is no need for the user to handle cryogenic liquids. When using refrigeration units such as these, a superconductive magnet coil winding, for example, is cooled indirectly only by thermal conduction to a cold head of a refrigerator, that is to say without any refrigerant (see also the cited text reference ICEC 16).

At the moment, superconductive magnet systems, in particular MRI (magnetic resonance imaging) installations, are generally cooled by bath cooling, in the case of helium-cooled magnets (see US 6,246,308 B1). A comparatively large amount of liquid helium, for example several hundred liters, has to be stored for this purpose. This amount of liquid helium leads to an undesirable buildup of pressure in a cryostat that is required when the magnet is quenched, that is to say during the transition from the parts of its winding initially being superconductive to the normally conductive state.

For LTC magnets, refrigerator cooling systems have already been produced using highly thermally conductive connections, for example in the form of copper tubes,

which may also possibly be flexible, between a cold head of an appropriate refrigeration unit, and the superconductive winding of the magnet (see the cited literature reference from ICEC 16, in particular pages 1113 to 1116). Depending on the distance between the cold head and the object to be cooled, the large cross sections which are required for good thermal coupling then, however, lead to

a considerable enlargement of the cold mass. Particularly in the case of magnet systems with a large physical extent, as are normally used for MRI applications, this is disadvantageous because of the extended cooling-down times.

Instead of thermal coupling such as this of the at least one winding to the at least one cold head via thermally conductive solid bodies, it is also possible to provide a line system in which a helium gas flow circulates (see, for example, US 5,485,730).

The object of the present invention is to specify a superconductor device having the features mentioned initially, in which the complexity for cooling a superconductive winding is reduced.

According to the invention, this object is achieved by the measures stated in claim 1. The thermal coupling means should accordingly be formed between the at least one winding and the at least one cold head should accordingly be in the form of a line system having at least one pipeline for a refrigerant which circulates in it on the basis of a thermosiphon effect. In this context, a cold head is any desired cold surface of a refrigeration unit via which the refrigeration power is emitted directly or indirectly to the refrigerant.

One such line system has at least one closed pipeline, which runs with a gradient between the cold head and the superconductive winding. The gradient at least in some parts of the pipeline is in this case generally more than 0.5°, preferably more than 1°, with respect to the horizontal. The refrigerant located in this pipeline recondenses on a cold surface of the refrigeration unit or of the cold head, and is passed from there to the region of the superconductive winding, where it is heated, and is in general vaporized in the process. The refrigerant vaporized in

this way then flows back again within the pipeline to the region of the

cold surface of the cold head. The corresponding circulation of the refrigerant accordingly takes place on the basis of the so-called "thermosiphon effect".

The use of a thermosiphon such as this (as a corresponding line system is also referred to) for transmission of the refrigeration power to the winding considerably reduces the amount of cryogenic refrigerant that has to be circulated in comparison to bath cooling, for example by a factor of about 100. Since, furthermore, the liquid circulates only in pipelines with a comparatively small diameter, which is in general in the order of magnitude of a few centimeters, the pressure buildup in the event of quenching can be coped with technically without any problems. In addition to the safety aspects, the reduction in the amount of liquid refrigerant in the system, particularly when using helium or neon as refrigerant, also has a considerable cost advantage. In comparison to cooling using thermally conductive connecting bodies, a thermosiphon also offers the advantage of good thermal coupling irrespective of the physical distance between the cold head and the object to be cooled.

Advantageous refinements of the superconductor device according to the invention are specified in the dependent claims.

By way of example, the line system may, in particular, have two or more pipelines which are filled with different refrigerants with a different condensation temperature. Appropriately graduated operating temperatures, for example for initial cooling, virtually continuous thermal coupling or virtually continuous thermal coupling by means of overlapping operating temperature ranges of the refrigerant are thus possible, depending on the requirement for the application. The subsystems may in this case be thermally coupled either to a common cold head

or else to separate cold heads of a refrigeration unit.

It is particularly advantageous for the superconductive magnet in the device to contain a winding made of superconductive HTC material and, in particular, also to be kept at a temperature below 77 K. A superconductor device according to the invention may of course, however, also be designed for LTC magnets.

Further advantageous refinements of the device according to the invention are disclosed in the dependent claims, which have not been discussed above.

Preferred exemplary embodiments of superconductor devices according to the invention will be explained in more detail in the following text with reference to the drawing in which case, in each case schematically and in the form of a section:

Figure 1 shows the cooling of an MRI magnet with two windings,

and

Figure 2 shows the cooling of a different MRI magnet with four windings.

The superconductor device which is annotated in general by 2 in Figure 1 and of which only those details which are significant to the invention are illustrated may, in particular, be part of an MRI magnet installation. In this case, this is based on embodiments which are known per se with a so-called C magnet (see, for example, DE 198 13 211 C2 or EP 0 616 230 A1). This installation therefore contains a preferably superconductive magnet 3, which will not be described in any more detail, with an upper superconductive winding 4a, lying on a horizontal plane, and a lower superconductive winding 4b, arranged parallel to the upper winding 4a. These windings may, in particular, be produced using conductors composed of high-T_c superconductor material such as $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$, which may be kept

at an operating temperature below 77 K for reasons associated with a high current carrying capacity. The windings are annular and are each accommodated in an appropriate vacuum housing, which is not illustrated.

The refrigeration power for cooling the windings 4a and 4b is provided by a refrigeration unit, which is not illustrated in any more detail and has at least one cold head 6 located at its cold end. This cold head has a cold surface 7, which must be kept at a predetermined temperature level, or is thermally connected to such a cold surface 7. The interior of a condenser chamber 8 is thermally coupled to this cold surface; for example with the cold surface 7 forming a wall of this area. According to the illustrated exemplary embodiment, the interior of this condenser chamber 8 is subdivided into two subareas 9a and 9b. A pipeline 10a of a pipeline system 10 is connected to the (first) subarea 9a. This pipeline first of all passes through the subarea 9a into the region of the superconductive winding 4a, where it makes good thermally conductive contact with the winding. For example, the pipeline 10a passes along the inner face of the winding, in the form of spiral turns. It is not essential for it to be fitted to the inner face; the only important factor is that the pipeline reaches the entire circumference of the winding with a permanent gradient, where it is thermally highly coupled to the parts or conductors of the winding to be cooled. At least the most important parts of the pipeline 10a include a gradient (or inclination) angle α of more than 0.5°, preferably of more than 1°, with the horizontal h. For example, the gradient angle α in the region of the winding 4a is thus about 3°. The pipeline 10a then leads into the region of the lower winding 4b, where it is arranged in a corresponding manner, and is closed at its end 11. The cross section q, which holds the refrigerant k1, of the pipeline 10a can advantageously be kept small and,

in particular, may be less than 10 cm^2. In the illustrated exemplary embodiment, q is about 2 cm^2.

The pipeline 10a, which is laid with a gradient, contains a first refrigerant k1, for example neon (Ne). The refrigerant k1 in this case circulates in the pipeline 10a including the subarea 9a, which is connected to it, on the basis of the thermosiphon effect, which is known per se. In the process, the refrigerant condenses in the subarea 9a on the cold surface 7, and is passed in liquid form into the region of the superconductive winding, where it is heated, for example at least partially being vaporized, and flows in the pipeline 10a back into the subarea 9a, where it is recondensed.

According to the illustrated exemplary embodiment, the line system 10 has a second pipeline 10b, which is routed parallel to the first pipeline 10a and is filled with a further refrigerant k2. This refrigerant is not the same as the first refrigerant k1, that is to say it has a different, preferably higher, condensation temperature. By way of example, nitrogen (N_2) may be chosen for the refrigerant k2. The pipeline 10b is in this case connected to the (second) subarea 9b of the condenser chamber 8. The second refrigerant k2 in this case likewise circulates in the closed pipeline 10b and in the subarea 9b on the basis of the thermosiphon effect. When the magnet windings are being cooled down, the second refrigerant k2 condenses first of all, in which case the windings may be precooled to about 70 to 80 K, for example by the use of N_2 as the refrigerant k2. As the cold surface 7 cools down further, the first refrigerant k1, which is located in the pipeline 10a, then condenses at the comparatively lower condensation temperature, thus leading to further cooling down to the intended operating temperature of, for example, 20 K (when neon is used as the first refrigerant k1). The second refrigerant k2 may be frozen in the region of the subarea 9b at this operating temperature.

In contrast to the exemplary embodiment illustrated in Figure 1, the superconductor device 2 according to the invention may, of course, also have only one line system with only a single pipeline. If a greater number of pipelines are envisaged, then two or more pipelines may also be thermally coupled to separate cold heads or to stages of a refrigeration unit at different temperature levels. In the case of two-stage refrigeration units or cold heads, as are planned in particular for cooling thermal plates, the magnet windings - in addition to being thermally linked to the second stage - would also be coupled to the first (warmer) stage for more rapid precooling by means of a further thermosiphon pipeline which, for example, is filled with nitrogen or argon.

The thermosiphon cooling described above may also, of course, be used for magnets which have vertically arranged windings. One exemplary embodiment of a device according to the invention with corresponding windings is illustrated in Figure 2. The device, which is annotated generally by 12, contains a superconductive magnet 13 in the form of a solenoid which, by way of example, has four superconductive windings 14j (where j = 1...4) located one behind the other in the axial direction. The individual windings are in this case, for example, each cooled on two end faces via pipelines 15i (where i = 1...8) which run at least substantially vertically and are filled, for example, with a refrigerant k1. Thus, in this case, there is no need for the spiral shape as in the exemplary embodiment shown in Figure 1, and the gradient angle α is approximately 90° over large parts of the line system, which is annotated generally by 20. A condenser chamber 18 and a cold head are in general arranged above the windings, in order in this way to ensure the necessary gradient. At least one pipeline 15i is required per winding since, in contrast to horizontally arranged windings, one pipeline cannot reach all the windings while maintaining the gradient.

In order to ensure that each pipeline 15i receives sufficient recondensed refrigerant k1, the entire pipeline system 20 formed by the pipelines 15i must either be in the form of a system of communicating pipes and be completely flooded with the liquid refrigerant in the region of the windings 14j. This is illustrated in Figure 2 by a blacker coloring of the refrigerant k1, while the vaporized regrigerant is shown in a lighter color, and is annotated k1'. Alternatively, each pipeline 15i must have a separate condenser (partial) chamber on the cold head.

A line system with pipelines which run parallel and are filled with different refrigerants (k1 and k2) may, of course, also be provided for the embodiment of the device 12 according to the invention illustrated in Figure 2.

In contrast to the illustrated exemplary embodiments, a superconductor device according to the invention may have a line system with at least one pipeline in which there is also a mixture of two refrigerants with different condensation temperatures. In this case, the gas with the highest condensation temperature can in consequence condense first of all during a gradual cooling-down process, and can form a closed circuit for heat transmission to a winding that is to be cooled. After precooling of this winding down to the triple-point temperature of this gas, this will then freeze in the region of the condenser chamber, following which the other gas mixture component with the lower condensation temperature ensures the rest of the cooling down process to the operating temperature.

Depending on the desired operating temperature, the gases He, H_2, Ne, O_2, N_2, Ar as well as various hydrocarbons may in practice be used as a refrigerant. The respective refrigerant gas is chosen such that

the refrigerant is gaseous and liquid at the same time at the intended operating temperature. This makes it possible to ensure circulation on the basis of the thermosiphon effect. The line system may have hot and/or cold equalization containers in order to specifically adjust the amount of refrigerant, while at the same time limiting the system pressure.

The choice of the refrigerant also, of course, depends on the superconductor material used. Only helium may be used as the refrigerant for an LTC material such as Nb_3Sn.